Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 54 (2014) 439 – 447
Energy Procedia

4th International Conference on Advances in Energy Research 2013, ICAER 2013

Operation of Solid Oxide Fuel Cell based Distributed Generation

Sangeeta Das*, Debapriya Das, Amit Patra

Department of Electrical Engineering,
Indian Institute of Technology Kharagpur 721302, India

Abstract

This paper presents the operation of a Solid Oxide Fuel Cell (SOFC) stack model based distributed generation (DG) by taking into consideration its dynamics. The SOFC modeling is carried out in state space form. The operation of this model in islanding as well as in grid connecting mode is discussed. The variations in the grid frequency and the output power delivered by the grid is presented for the both the modes. Effectiveness of the SOFC model has been demonstrated by connecting it to an infinite bus and to a 10 node distribution network. Voltage profile improvement and power loss reduction play a key role in distribution network. Results confirm the usefulness of this model in improving the voltage profile and in maintaining the grid frequency.

Selection and peer-review under responsibility of Organizing Committee of ICAER 2013
*Keywords:*SOFC model, Distributed Generation, Distribution network, Grid connecting mode, islanding mode

1. Introduction

Distribution networks Distribution networks play a key role in the electrical market as it is on the consumer side. Customer satisfaction is based on the reliability and the quality of the electricity supplied. To improve the voltage profile and to reduce the active power losses, researchers all across the globe have put in all their efforts to overcome this problem. Time and again, the integration of compensators into the distribution network or the reconfiguration of the network has proved to be successful. However, in the 21st century, with the electricity market getting deregulated, an endless opportunity was available to play with the distribution networks. And this era began with the incorporation of distributed generations (DGs) in the distribution network. DGs have changed the way distribution networks looked like.

* Corresponding author. Tel.: +91-3222-283042;
E-mail address: sang2409@gmail.com

Selection and peer-review under responsibility of Organizing Committee of ICAER 2013
doi:10.1016/j.egypro.2014.07.286

The passive, radial structure is gone. The networks have become active with DGs allowing the current to flow in either direction. The penetration of distributed generation in utility networks is increasing worldwide. The presence of generation close to demand can potentially reduce the need for traditional system expansion. This eventually led to the concept of microgrids. Microgrids are independent low voltage or medium voltage distribution networks comprising of micro sources, energy storages and controllable loads.

Zhu and Tomsovic [1] proposed simplified slow dynamic models for fuel cells along with the analysis of their stand- alone dynamic performance. Padulles, Ault and McDonald [2] proposed a simulation model of a power plant based on fuel cell using PSS commercial package. He [3] presented a simulated model of the fuel cell to determine the load following capability of the system. Das, Aditya and Kothari [4] presented the dynamics of wind turbine generators and diesel considering the optimum values of the gain settings of the proportional integral controller. Mioa, Domijan Jr. and Fan [5] investigated the stability of a microgrid with diesel generator and inverter based distributed energy resources under islanded conditions. Gao and Iravani [6] proposed a voltage controlled voltage sourced converter model to study the operation of distributed generators in grid connected and islanded modes. Lopes, Moreira and Madureira [7] proposed two control strategies to study the dynamic behavior of the inverter fed microgrid under islanded operation. Various other literature relating to the work in this field [8-14] are studied.

This paper presents the modeling of a SOFC stack taking into consideration its dynamics. The operation of the modeled SOFC stack is studied in islanding as well as grid connecting mode. The state space approach is carried out to model the stack. The operation of the SOFC stack is analyzed using two approaches: (a) Connected to the grid, (b) Connected to a 10 node sample distribution network [15].

2. SOFC Stack Model

Fuel cells are another rapidly developing generation technology [1]. They have the high efficiency and high reliability due to the limited number of moving parts. The effectiveness of a fuel cell lies in the electrolyte used. The classification of the fuel cells is based on the type of the electrolyte used. Polymer electrolyte fuel cell (PEFC), Alkaline fuel cell (AFC), Phosphoric acid fuel cell (PAFC), Molten carbonate fuel cell (MCFC) and Solid oxide fuel cell (SOFC) are some of its types. Out of the many, the modeling of SOFC is discussed in detail.

2.1. Background

The reaction of hydrogen with oxygen to produce water is the basic fundamental operation of all fuel cells [2]. In an SOFC, these half reactions take the form,

$$H_2 + O^{-2} \rightarrow H_2O + 2e^- \text{ … anode} \tag{1}$$

$$O_2 + 4e^- \rightarrow 2O^{-2} \text{ … cathode} \tag{2}$$

The electrons released in the anode half reaction flow through an external circuit as current and return to the cathode to react with oxygen molecules. The thermal dynamics are not included as the associated time constants are much longer than those of the electrochemical response. The fuel supplied to the SOFC plant is natural gas.

2.2. Assumptions

- The only source of losses is ohmic.
- The Nerst equation can be applied.

2.3. Modeling

It could be considered that the molar flow of any gas through the valve is proportional to its partial pressure inside the channel, according to the expressions.

$$\frac{q_{H_2}}{p_{H_2}} = \frac{K_{an}}{\sqrt{M_{H_2}}} = K_{H_2} \tag{3}$$

$$\frac{q_{H_2O}}{p_{H_2O}} = \frac{K_{an}}{\sqrt{M_{H_2O}}} = K_{H_2O} \tag{4}$$

$$\frac{q_{O_2}}{p_{O_2}} = \frac{K_{an}}{\sqrt{M_{O_2}}} = K_{O_2} \tag{5}$$

where K_{an} : anode valve constant.

$q_{H_2}, q_{H_2O}, q_{O_2}$: Molar flows of hydrogen, water and oxygen respectively.

$K_{H_2}, K_{H_2O}, K_{O_2}$: Valve molar constants for hydrogen, water and oxygen respectively.

The universal gas equation is applied to every individual gas and in this section, hydrogen is considered as an example.

$$p_{H_2}.V_{an} = n_{H_2}.R.T \tag{6}$$

where V_{an} : Volume of the anode.

n_{H_2} : Number of hydrogen moles in the anode channel.

R : Universal gas constant

T : Absolute temperature.

Isolating the pressure and taking the time derivative of the expression, one obtains,

$$\frac{d}{dt} p_{H_2} = \frac{R.T}{V_{an}} q_{H_2} \tag{7}$$

where q_{H_2} : time derivative of n_{H_2} which represents the hydrogen molar flow.

There are three relevant contributions to the hydrogen molar flow:

$\rightarrow$ The input flow, $q_{H_2}^{in}$

$\rightarrow$ The flow that takes part in the reaction, $q_{H_2}^{r}$

$\rightarrow$ The output flow, $q_{H_2}^{out}$

So, eqn. (7) can be written as

$$\frac{d}{dt} p_{H_2} = \frac{R.T}{V_{an}} \left[q_{H_2}^{in} - q_{H_2}^{out} - q_{H_2}^{r} \right] \tag{8}$$

According to the basic electrochemical relationship, the molar flow of hydrogen that reacts can be calculated as,

$$q_{H_2}^{r} = \frac{N_O.I}{F} = 2K_r.I \tag{9}$$

where N_O : Number of cells associated in series in the stack,

F : Faradays constant,

K_r : Constant equal to $\dfrac{N_O}{2F}$.

The hydrogen partial pressure becomes,

$$\frac{d}{dt}p_{H_2} = \frac{RT}{V_{an}}\left(q_{H_2}^{in} - q_{H_2}^{out} - 2K_r.I\right) \tag{10}$$

Taking the Laplace transform,

$$p_{H_2} = \frac{1/K_{H_2}}{1+\tau_{H_2}s}\left(q_{H_2}^{in} - 2K_r.I\right) \tag{11}$$

where $\tau_{H_2} = \frac{V_{an}}{K_{H_2}.R.T}$, in seconds.

Similar expressions can be drawn for H_2O at anode channel and O_2 at the cathode channel.

2.4. SOFC Stack Equations

The SOFC can be modeled in state space form,

$$\dot{X} = AX + B.I_{dc} \tag{12}$$

The matrices A and B can be written as,

$$A = \begin{vmatrix} -\frac{1}{\tau_{H_2}} & 0 & 0 & \frac{1}{\tau_{H_2}.K_{H_2}} \\ 0 & -\frac{1}{\tau_{H_2O}} & 0 & 0 \\ 0 & 0 & -\frac{1}{\tau_{O_2}} & \frac{r_{H\_O}}{K_{O_2}.\tau_{O_2}} \\ 0 & 0 & 0 & -\frac{1}{T_f} \end{vmatrix} \qquad B = \begin{vmatrix} -\frac{2K_r}{\tau_{H_2}.K_{H_2}} \\ \frac{2K_r}{\tau_{H_2O}.K_{H_2O}} \\ -\frac{K_r}{\tau_{O_2}.K_{O_2}} \\ \frac{2K_r}{U_{opt}.T_f} \end{vmatrix}$$

The expressions for V_{dc} and I_{dc} are given by

$$V_{dc} = N_O E_O + \frac{N_O RT}{2F}\left[\ln\frac{p_{H_2}.\sqrt{p_{O_2}}}{p_{H_2O}}\right] \tag{13}$$

$$I_{dc} = K_m \int \frac{(P_{gen} - P_{set})}{V_{rated}}dt \tag{14}$$

and are obtained from the model in figure 1, where V_{dc}, I_{dc} are the stack voltage and the stack current respectively.

2.5. Inverter Interface

Many of the newer forms of distributed generation cannot be connected directly to the AC grid [16]. Fuel cells and solar cells effectively generate at DC. Grid connection, therefore, requires a power electronic interface. The fuel cell supplies energy to the DC bus via a DC-DC converter, which acts as a current regulator. A DC-DC converter is used to step up the voltage of the fuel cell stack to that of the dc bus, and to provide regulation of the DC bus voltage and of the fuel cell current. ***The switching dynamics are not modeled.***The primary contr ol objectives for the inverter are to deliver a specified active power to the grid and to regulate the terminal voltage to a pre-established set point.

2.6. Phase Locked Loop

Microgrids that are supplied solely by inverter based sources, such as fuel cells, may have no rotating inertia. As a result, the frequency of the AC voltages and currents must be established by the inverter. This can be achieved by the use of a phase locked loop (PLL). A reference signal for firing is established by the PLL [17]. The dynamic behavior of the PLL, therefore, has an important influence on the microgrid frequency.

2.7. Complete Model

The complete model comprises of the SOFC model incorporated with the inverter controls and the phase locked loop. The block diagram representation of the complete model is presented in figure 2.

3. Studied System

In order to study the effect of the SOFC based DG on the distribution network, three cases are considered with the incorporation of SOFC into the system. Firstly, the complete model is integrated to the grid. The grid is assumed to be an infinite bus. The load is taken to be 170 kW. The schematic representation of this case is presented in figure 1. The block representation of the grid along with the SOFC based DG is shown in figure 3. Secondly, a 23 kV, 100 MVA, 10 node sample distribution network is considered [15]. The SOFC based DG is connected to the 5^{th} node of the 10 node distribution network to study the changes in voltage profile, which is shown in figure 4. Thirdly, two SOFC based DGs are considered which are connected to node 5 and node 10 to study the usefulness of the model.

Fig.1. Single line diagram of the microgrid study system

4. Results and Analysis

4.1. Case 1

The result of the SOFC stack connected to an infinite bus is presented in figure 5. The result shows the changes in four different parameters. The analysis of the results can be divided into three phases: (i) SOFC connected to the grid (0 – 20 s), (ii) islanded conditions (20 – 40 s) and (iii) resynchronization with the grid (40 s onwards). The output voltage of the SOFC stack at steady state point is 2 p.u. The voltage refers to 480 V on a base of 240 V. The terminal voltage is 1p.u. on the same voltage base. These two parameters remain the same in all three phases.

During the first phase, the power delivered by the SOFC stack is 70 kW. It is 0.7p.u. on a 100 kW base. As the load is of 170 kW, the remaining 100 kW is powered by the grid. The grid frequency initially drops due to the sudden demand in load and becomes nominal after few seconds. The secondary control is functional as the grid is still connected. During the second phase, the SOFC is disconnected from the grid and goes into islanded mode. The power supplied by the grid to the load becomes zero. Hence, the total power of 1.7p.u. on a 100 kW is fed to the load by the SOFC stack. The grid frequency momentarily shoots up due to the loss in the load and finally becomes nominal. The secondary control is no more functional in this phase as the grid has to supply no more power. During the third phase, the SOFC is resynchronized to the grid. The output power of the SOFC drops as a part of the power is now fed by the grid. The grid frequency and the secondary control exhibit the same feature as during the first phase.

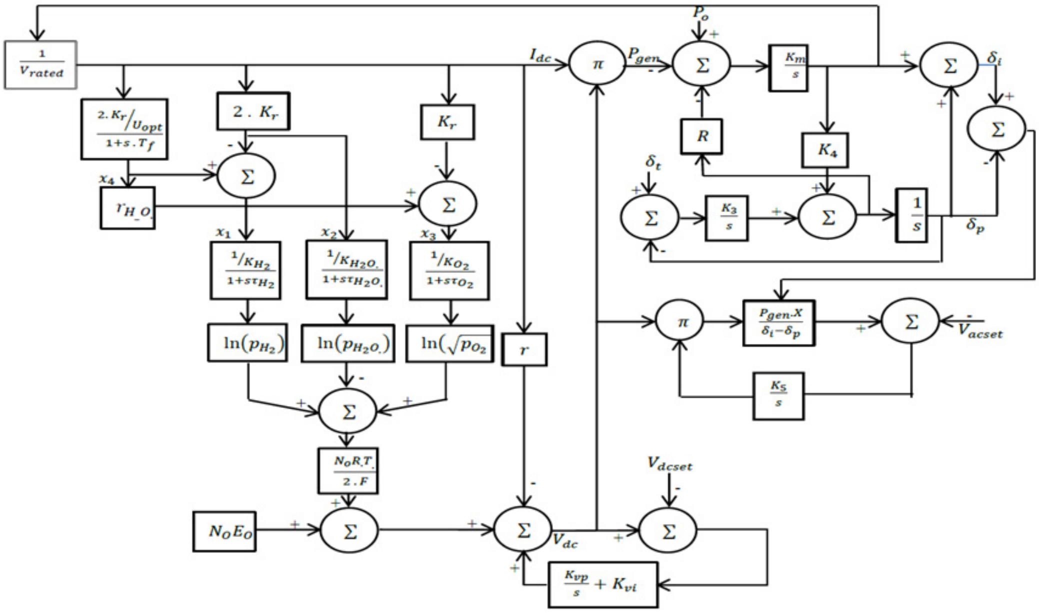

Fig.2. Complete Modeling

4.2. Case 2

The result of the SOFC stack connected to a 10 node sample distribution network is presented in figure 7. Data for this system are available in [15]. The DG is connected at node 5 of the network. The sudden changes in the voltage at two different nodes are observed. The voltage keeps on changing till it reached the steady state. The converged voltage values at node 5 and node 10 without SOFC are 0.9480p.u. and 0.8375p.u. which is presented in figure 6. After placement of the SOFC, the converged voltage values are found out to be 0.9485p.u. and 0.8381p.u. respectively. From the results, it can be observed that there has been a small improvement in the voltage profile.

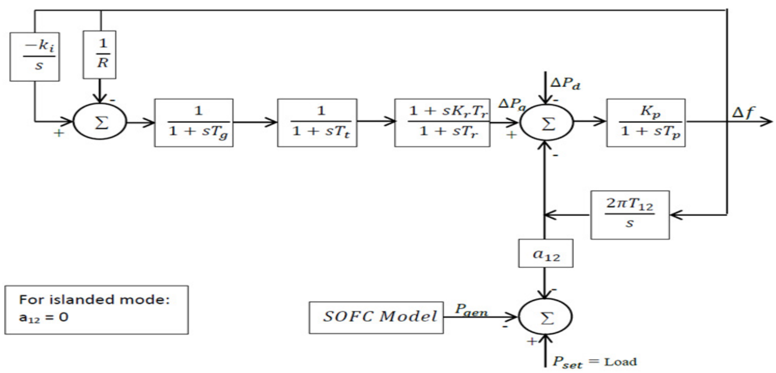

Fig.3. Block Representation of the grid.

4.3. Case 3

In this case, two SOFCs are connected to the distribution network (node 5 and node 10). After placement of the SOFCs, the converged voltage values are found out to be 0.94918p.u. and 0.84252p.u. respectively (figure 8).

5. Conclusions

In this paper, the emerging concepts of microgrids have been studied successfully. Out of the many available micro-sources, the solid oxide fuel cell has been modeled and integrated to the utility grid. The P-Q control mode of the DG has been successfully studied. Of the three cases studied, it has been seen that the SOFC model has been successful in maintaining the grid frequency of an infinite bus as well as helps in improving the voltage profile of the distribution network.

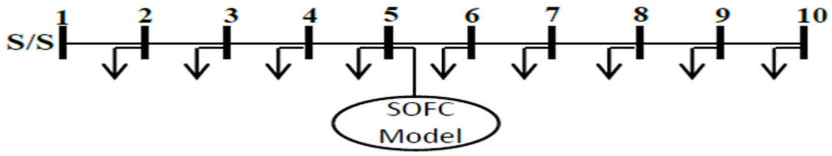

Fig.4. SOFC connected to node 5 of the distribution network

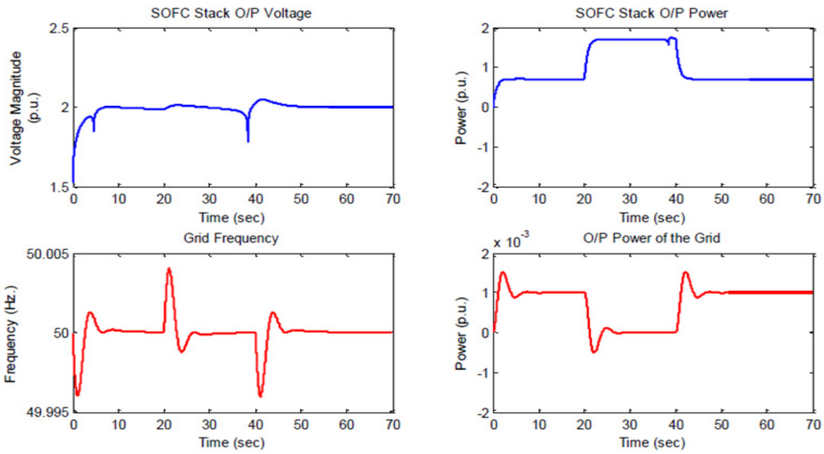

Fig.5. Results of the SOFC based DG connected to an infinite bus

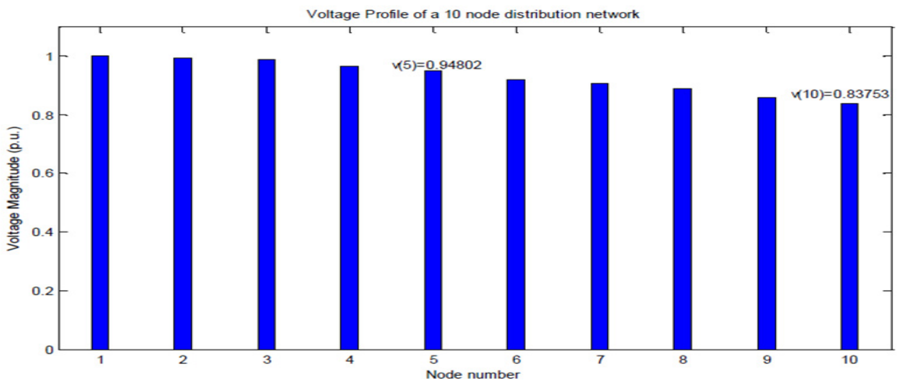

Fig.6. Voltage profile of a 10 node distribution network without SOFC

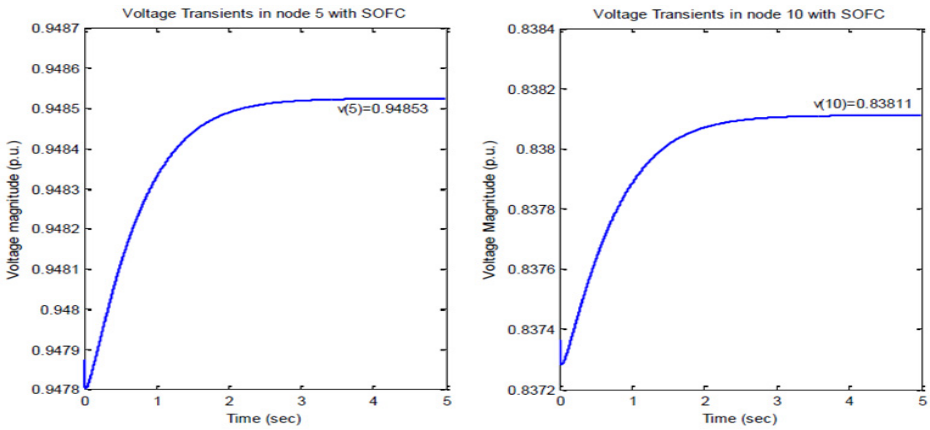

Fig.7. Results of the SOFC based DG connected to node 5 of the distribution network

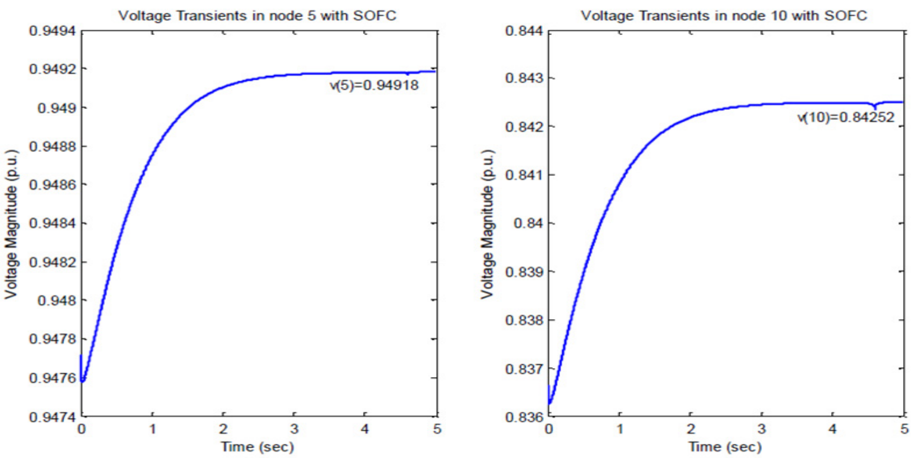

Fig.8. Results of the SOFC based DG connected to node 5 and node 10 of the distribution network

Appendix

Data for the SOFC model: K_r = 0.996 * 10^(-6), r = 0.126 Ω, K_{H_2} = 8.43 * 10^(-4), τ_{H_2} = 26.1 s, K_{H_2O} = 2.81 * 10^(-4), τ_{H_2O} = 78.3 s, K_{O_2} = 2.52 * 10^(-3), τ_{O_2} = 2.91 s, N_O = 384, E_O = 1.18 V, R = 3814, T = 1273.15 K, F = 96487 C/mol, U_{opt} = 0.85, P_{set} = 0.7 p.u., V_{rated} = 333.8 V, r_{H_O} = 1.145, V_{dcset} = 480 V, K_{vp} = -0.5, K_{vi} = -0.05, T_g = 0.08 s, T_t = 0.30 s, T_r = 10 s, K_r = 0.50, K_p = 120, R = 2.40 Hz/puMW, T_p = 20 s, K_I = 0.67, T_{12} = 0.0866.

References

[1] Zhu, Y. and Tomsovic, K. Development of models for analyzing the load following performance of microturbines and fuel cells. Electric Power Systems Research; 2002. 62.p. 1-11.
[2] Padulles, J., Ault, G.W. and McDonald, J.R. An integrated SOFC plant dynamic model for power systems simulation.Journal of Power Sources;2000.84. p. 495-500.
[3] He, W. Dynamic model for molten carbonate fuel cell power generation systems.Journal of Energy Conversion Manag; 1998.39(8).p. 775-783.
[4] Das, D., Aditya, S.K. and Kothari, D.P. Dynamics of diesel and wind turbine generators on an isolated power system.Electrical Power and Energy Systems;1999.21.p. 183-189.
[5] Mioa, Z., Domijan Jr., A. and Fan, L. Investigation of Microgrids with both inverter interfaced and direct AC connected distributed energy resources.IEEE Transactions on Power Delivery; 2011.26(3).p. 1634-1642.
[6] Gao, F. and Iravani, M.R. A control strategy for a distributed generation unit in grid connected and autonomous modes of operation.IEEE Transactions on Power Delivery;2008.23(2).p. 850-859.
[7] Lopes, J.A.P., Moreira, C.L. and Madureira, A.G. Defining control strategies for microgrids islanded operation.IEEE Transactions on Power Apparatus and Systems; 2006.21(2).p. 916-924.
[8] Liu, X.J. and Chan, C.W. Control of a solid oxide fuel cell power plant in a grid connected system. IEEE Transactions on Energy Conversion; 2007.22(2).p. 405-413.
[9] Rahman, M.A. and Osheiba, A.M. Modeling of Permanent Magnet Synchronous Generators.Proceedings of the ICEM'88,Pisa, Italy;1988.p. 45-51.
[10] Hadjsaid, N., Canard, J.F. and Dumas, F. Dispersed generation impact on distribution networks.Computer Applications in Power.1999.12(2).p.22-25.
[11] Katirei, F., Iravani, M.R. and Lehn, P.W. Microgrid Autonomous Operation During and Subsequent to Islanding Process.IEEE Transactions on Power Delivery;2005.20(1).
[12] Pogaku, N., Prodanovic, M. and Green, T.C. Modeling, Analysis and Testing of Autonomous of an Inverter Based Microgrid.IEEE Transactions on Power Delivery, 2007.22(2).p. 613-625.
[13] Katirei, F., Iravani, M. and Lehn, P. Small signal dynamic model of a micro grid including conventional and electronically interfaced distributed resources. Inst. Eng. Technol. Gen. Transm. Distrib.; 2007.1(3).p. 369-378.
[14] Piagi, P. and Lasseter, R.H. Autonomous Control of Microgrids. Power Engg. Society General Meeting, Montreal. QC, Canada; 2006.
[15] Baran, M.E. and Wu, F.F. Optimal sizing of capacitors placed on a radial distribution system, IEEE Transactions on Power Delivery,1989.4(1).p. 735-743.
[16] Hiskens, I.A and Fleming, E.M. Control of Inverter Connected Sources in Autonomous Microgrids. 2008 American Control Conference, USA;2008.June 11-13.
[17] Abramovitch, D. Phase Locked Loops: A control centric tutorial. Proceedings of the American Control Conference, Anchorage, AK.